Geo-location White Space Spectrum Databases: Models and Design of South Africa's First Dynamic Spectrum Access Coexistence Manager

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Abstract

Geo-location white space spectrum databases (GL-WSDBs) are currently the preferred technique for enabling spectrum sharing between primary users and secondary users or white space devices (WSDs) in the very-high frequency (VHF) and ultra-high frequency (UHF) bands. This is true because technologies for making low-cost WSDs capable of autonomous sensing and detection of available white space (WS) spectrum are not yet feasible. This paper reviews the necessary enabling technical conditions to allow coexistence of primary and secondary systems in the VHF and UHF spectrum through a GL-WSDB approach. The practical implementation of South Africa's first GL-WSDB was performed. Results of WS channels available from five cities in South Africa calculated from the implemented GL-WSDB was compared with a commercially available GL-WSDB and was found to be 68% similar. Additionally, results from the implemented GL-WSDB were compared with measurements obtained from field spectrum scanning campaigns at two different locations in Cape Town, South Africa, and was found to be 64% similar.

Keywords: Primary Users, Spectrum Database, GL-WSDB, WSD, TVWS

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1. Introduction

This paper discusses the concept of geo-location white space spectrum databases (GL-WSDBs) as an enabling technology for spectrum sharing. GL-WSDB is presented as a coexistence manager of white space devices (WSDs), white space broadband networks (WSBNs) and licensed spectrum networks. The paper discusses step-wise methodological approaches and algorithms for designing national white space spectrum database systems. The focus is placed on the very high frequency (VHF) and ultra-high frequency (UHF) bands, with the possibility to extend it to other useful radio frequency bands of interest. The main contributions of the paper are twofold. Firstly, to highlight the exact functional position and role of GL-WSDBs within terrestrial broadcasting TV networks architecture, examining terrestrial broadcasting TV network planning models, methodologies and parameters. Secondly, the paper focuses on the practical development of GL-WSDBs, explaining the computational technical parameters and policy aspects required for enabling secondary users to utilize white space spectrum without causing any harmful interference to the incumbent users. Furthermore, results of a GL-WSDB system developed by the CSIR- Meraka Institute are presented.

The results are evaluated using two methods. Firstly, comparison with a selected commercially available GL-WSDB and secondly comparison with spectrum occupancy scanning measurements that were performed in the field. The remainder of the paper is arranged as follows: Section 2 provides the motivation of the study. In Section 3, we review national terrestrial broadcast TV panning models. Section 4 introduces GL-WSDB parameters, while Section 5 reviews GL-WSDB implementation methodologies. Section 6 discusses the practical implementation. Section 7 presents results and discusion. Section 8 evaluates the results and Section 9 concludes the paper. **Fig. 1** describes a typical TVWS network as an overlay on a broader terrestrial broadcast TV network. Fixed WSDs query the GL-WSDB to access locally available TV channels in order to provide wireless broadband Internet connectivity to unserved or underserved areas.

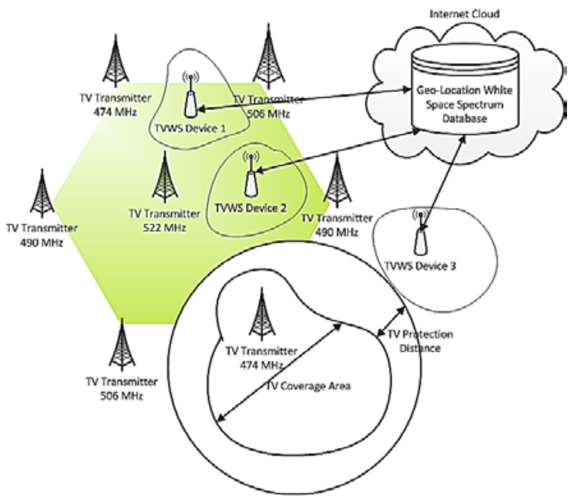

Fig. 1. Geo-location white space spectrum database in a UHF band terrestrial broadcast TV network structure.

2. Motivation

Radio frequency (RF) spectrum is a precious non-depleting but limited wireless national information and communication technology (ICT) infrastructure resource. RF spectrum enables wireless devices to communicate. Therefore spectral utilisation efficiency is a major pillar towards the realisation of a successful national broadband policy. The forecasted demand for RF spectrum needed for mobile and other wireless services is projected to increase rapidly in the next five years [1]. This demand creates an urgent need for more RF spectrum. At the same time, however, spectrum audit measurement reports in many parts of the world have shown that there is a great under-utilisation of this resource. For example, spectrum audit measurements conducted in South Africa's five major cities by the Independent Communications Authority of South Africa (ICASA) reveals gross under-utilisation of the allocated UHF spectrum by up to 99% [2]. Wireless access technologies are seen as an alternative, cost effective means of communication over fixed-line or wired infrastructure in developing regions, where traditionally there is little or no wired infrastructure. To achieve this, national spectrum regulators particularly in developing countries need to start implementing policy measures necessary for the adoption of efficient dynamic spectrum allocation and utilisation. In so doing, regulators will accommodate the emerging dynamic spectrum access (DSA) technologies necessary to keep up with growing demand for spectrum needed for mobile and wireless services and bridging the so-called digital divide.

A lot is already known about DSA, TVWS communications, and GL-WSDBs, particularly in the developed countries [3 - 6]. However, much of this research does not directly consider factors relevant to developing region contexts. GL-WSDB technologies are currently the only practical spectrum access systems (SAS) for enabling WSDs in establishing WSBNs for providing broadband Internet connectivity over TV bands. This is because WSDs capable of autonomous spectrum sensing are not reliable enough in protecting primary users. TV band spectrum has superior propagation characteristics, penetrating man-made and natural obstacles and possessing longer range. This makes WSBNs a suitable choice for connecting the rural under-served and un-served areas with low population densities where mainstream mobile and other wireless services operators are reluctant to serve.

3. Review of Terrestrial Television Planning Models

Constructing a national geo-location whitespace spectrum database requires one to have knowledge of an incumbent national terrestrial television-planning model well in advance. Broadly speaking, the national planning model outlines worst-case technical conditions sufficient to ensure quality coverage at the edge of a reference network (RN) as well as protecting incumbent transmitters from any harmful interference. Such technical conditions can be extracted from empirical measurements (i.e., field strength curves) [7] or derived from calculated statistical approximations [8].

3.1 Reference Planning Configurations

Strictly speaking, the models discussed above assist a GL-WSDB constructor to understand the typical reference planning configurations (RPCs) that have been utilised for each scenario in a particular terrestrial TV broadcast geographical coverage area. RPCs are results of deliberations stemming from the radio regulations (RR) of the International

Telecommunications Union (ITU), the ITU regional radio communication conferences (RRCs) [9], ITU multilateral agreements, as well as unilateral (country-specific) decisions [10], [11]. The key approaches defined by the RPCs generally relate to the configuration geometries of the terrestrial broadcast TV stations transmitter-receiver pairs; the most commonly used such geometries are: (1) Fixed outdoor reception geometry: This configuration assumes a rooftop TV receiving antenna height of 10 m above ground level (AGL). (2) Portable/or mobile outdoor geometry: This configuration assumes an outdoor receiving TV antenna height of 1.5 m AGL. (3) Portable indoor geometry: This configuration assumes an indoor TV receiving antenna height of 1.5 m AGL. It is important to note that RPC geometries are classified according to the TV transmission technology to be used. The two dominant transmission technologies are analogue and digital; in most cases analogue technology is only used for rooftop reception scenarios while digital technology is used for fixed reception and portable/mobile reception scenarios. Furthermore, the RPCs also specify parameters such as the reference frequency, the criteria for TV receiving locations probability, the tolerable interference and the minimum median field strengths in the VHF and UHF bands for each scenario.

3.2 Terrestrial Broadcast Television Network Structures

A typical terrestrial television network consists of a plurality of transmitter sites located in the geographical areas to be covered. These transmitters have varying heights and powers ranging from high-power transmitters to very low-power transmitters. Usually the high-power sites are used as the main transmitters to the respective targeted geographical market. Main transmitters are sometimes supplemented with the low-power relay sites that are used for the purpose of gap-filing the planned coverage areas within which the TV transmission from the high-power sites is received with low quality below the desirable minimum threshold. The low-power sites are categorised into two main types: (1) Sites that are owned by the broadcaster (2) Sites that are owned by a particular community for the purpose of enhancing the reception quality from a particular TV broadcasting network. Furthermore, terrestrial TV networks are usually configured into two distinct topologies:

- The Single frequency network (SFN): In this topology all transmitters in a particular network are configured to utilise the same frequency in a delay-synchronized manner; that is the time taken for a broadcast signal from transmitters in a SFN to a receiver must falls within the pre-defined guard interval. Therefore, the signal with shorter delay time is treated as wanted while that with longer delay time is treated as unwanted. All transmitters in the SFN broadcast identical content nationally or in different geographical areas. That is, they are using the same channel for providing a continuous coverage. Existing technologies makes it unfeasible to implement regional or local-specific programming, as this will require a break-up from the national wide SFN channel. However, several SFNs can re-use the same frequencies at a separation distance that is safe not to cause harmful interference to each other. SFN topology is mostly suited for use in the digital TV transmission technologies. **Fig. 2** illustrates this further.

- The multiple frequency network (MFN): In this topology transmitters in a particular network are configured to utilise different frequencies in different geographical areas. That is they are using different channels for providing coverage when broadcasting same or different content. Regional-specific broadcasting is possible under this topology.

MFNs are structured in such a way that channels assignments plans are performed in uniform lattice systems to avoid interference in the adjacent channels and to provide safe re-use separation distances for co-channels. MFNs topology is most prevalent in the analogue TV transmission technology and during the analogue to digital migration period. Structures of a SFN and MFN are illustrated in **Fig. 2a)** and **Fig. 2b)**.

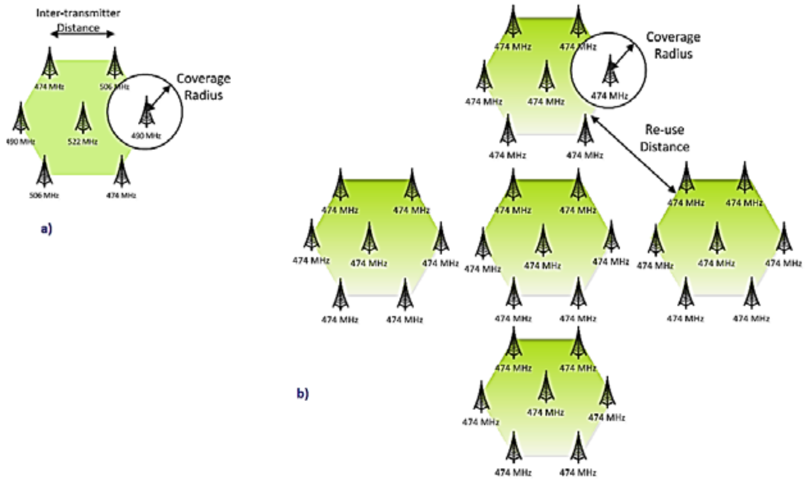

Fig. 2a) Structures of multiple frequency network and, **Fig.2b)** multiple single frequency networks

3.3 Terrestrial Broadcast Television Networks Coverage Modes

A coverage area in terrestrial broadcast TV is broadly defined as the geographical area within which the wanted field strength measured at a receiving location is greater than or equal to the minimum median field strength (this is the minimum value of the field strength necessary to permit a desired reception quality, under specified reception conditions). There are two approaches used to characterize the mode of coverage areas as a function of the quality of service received by the TV viewers located within the particular coverage area:

- Noise limited contour (NLC) approach: This approach defines an area (contour) for a TV transmitter where TV receivers can receive a TV signal and where incumbent TV receivers need to be protected from harmful interfering noise from other TV transmitters or other devices using the same radio frequency. The generation of noise from transmitters using same frequency can be described as network self-interference. The coverage of the NLC is an area within which the pre-defined minimum carrier-to-noise-ratio (CNR) threshold is satisfied by the difference between the minimum wanted signal power and the receiver noise floor.

- Interference limited contour (ILC) approach: This is an approach that allows the new assignments of multiple radio frequencies to multiple TV broadcast transmitters based on a principle of inter-transmitter separation distance with respect to the existing transmitters. Such new assignments can cause tolerable interference to the existing TV viewers or vice versa. The coverage of an ILC is therefore defined as an area within which the pre-defined minimum carrier-to-noise-plus-interference-ratio (CNIR) threshold is satisfied by the difference between the minimum wanted signal power and the interfering signal power.

Moreover, it is important to note that in the analogue terrestrial TV transmission technology; the signal-to-noise-ratio *(SNR)* is 8.047 *dB* less than that of the *CNR* [8]. For brevity, the difference between the two ratios is due to the fact that the *SNR* is a result of measurements taken at the output of the demodulator and is expressed as a ratio of the peak-to-peak video baseband signal voltage (typical value for the PAL-I standard is *0.7 V* and *0.714 V* for the NTSC standard) to the noise bandwidth of the video signal [12]. *CNR* On the other hand is the ratio of the RF carrier power to the noise at the transport path (i.e., measured at the input of the receiver).

3.4 Terrestrial Broadcast Television Protection Ratios

In general terms, protection ratios are the minimum required signal threshold levels necessary to protect terrestrial TV from any harmful interference in order to provide the desired signal quality. As discussed in sub-Section 3.3, the ratios: (CNR, CNIR, CIR, SNR), as well as the noise to interference plus noise ratio (NINR), and the interference to noise ratio (INR) are hereby referred to as protection ratios. It is worth noting that these ratios are standard and technology-specific that is, various analogue and digital TV standards have different values of protection ratios [13], [14], and [15].

3.5 Radio Propagation Models

Radio propagation models are the crucial tools in a national terrestrial broadcast TV planning model. The models are used to predict the worst-case scenarios for path losses, the received signal power or field strength at the receiver. Generally, radio propagation models are categorised according to their specific usage and a suitable model must be selected for each planning scenario. Furthermore some propagation models take into account the physical characteristics of the terrain profile and clutter between the transmitter and the receiver while other models do not. **Table 1** lists popular radio propagation models and their specific usage.

Table 1. Illustration of selected propagation models [16].

Model	Frequency Range	Distance	Category	Typical Application
Extended Hata	0.03 GHz – 3 GHz	Up to 40 km	Empirical	Point-to-point short –to- medium range planning of terrestrial broadcast station with short-to-medium height antennas. Uses measured terrain data in the form of curves.
Longley-Rice [17]	0.02 GHz – 40 GHz	1 km – 2000 km	Mixed: Empirical/Deterministic	**Point-to-averaged-radial** and point-to-multipoint planning and generic coordination- planning of terrestrial broadcast stations. Uses terrain profile elevation and measured data.
ITU-R P.1546-5	0.03 GHz– 3 GHz	1 km – 1000 km	Mixed: Empirical/Deterministic	Point-to-multipoint generic coordination –planning of Terrestrial broadcast stations. Uses measured terrain data in the form of curves and terrain profile elevation 3 – 15 km from the transmitter.
TM-91-1 [18]	0.04 GHz – 1 GHz	Less than 16 km	Empirical	Point-to-point planning for short distances.
ITWOM [19]	0.02 GHz – 20 GHz	1 km – 2000 km	Mixed: Empirical/Deterministic	Point-to-point and point-to-multipoint planning of terrestrial broadcast stations. Uses terrain profile elevation and measured data.

- Deterministic propagation models: These models predict the transmitted power or field strength from the radiating center of the transmitter to the height of the receiver taking into account the physical path terrain elevation profile. The models also take into account the free space losses and diffraction losses along the path. Therefore, these models are suitable for site-specific planning scenarios where high precision prediction is required.

- Empirical propagation models: These models also referred to as statistical; predicts the transmitted power or field strength from the radiating center of the transmitter to the height of the receiver independent of the physical path terrain elevation profile. Largely, the calculations in these models rely on the physical data obtained from extensive measurement campaigns from different geographical locations and environmental conditions. The models have minimum reliance on terrain elevation profile data. Therefore, these models are suitable for general planning and coordination scenarios where high precision prediction is not required.

- Mixed propagation models: These models are considered to possess both the deterministic and empirical characteristics.

Table 2. Performance comparison of selected propagation models using Monet Carlo simulations on flat Earth.

Scenario 1: Frequency = 650 MHz, Transmitter Height = 90 m, Receiver Height = 10 m, Distance = 1 m = 100 km, Number of Samples = 10000			
Propagation Model	Mean Path Loss (dB)	Median Path Loss (dB)	Standard Deviation Path Loss (dB)
ITU-R P.452-14	140.49	143.34	23.04
ITU-R P.1546-4	157.55	162.61	20.34
Extended Hata	126.47	127.55	16.29
Longley-Rice	145.03	150.54	24.08
Scenario 2: Frequency = 650 MHz, Transmitter Height = 5 m, Receiver Height = 1.5 m, Distance = 1 m – 1.5 km, Number of Samples = 10000			
Propagation Model	Mean Path Loss (dB)	Median Path Loss (dB)	Standard Deviation Path Loss (dB)
ITU-R P.452-14	89.13	91.14	15.08
ITU-R P.1546-4	100.79	104.30	13.95
Extended Hata	98.15	101.10	9.95
Longley-Rice	83.68	86.28	8.54

3.6 Terrestrial Broadcast Television Antennas: Patterns, Polarizations, and Pointing

Two types of antennas are used in terrestrial broadcast TV: (1) transmitting antennas and, (2) receiving antennas. Furthermore, antennas can be characterised according to their frequency band of operation (band-specific) or non-band specific ones (wideband). As well as their directivity: (1) directional antennas and, (2) non-directional antennas (Omni directional). The gains and directivity discrimination of terrestrial broadcast TV receiving antennas are described in [20]. **Table 3** compares typical gains of the most commonly used band-specific and wideband DTT receiving antennas found in South Africa [21].

Table 3. Comparison of antenna gain (in dBd) of most commonly used sub-band specific and wideband DTT receiving antennas in South Africa [21].

Frequency	Gain (dBd)	
	Sub-band specific antenna	Wideband antenna
470 - 600	10.179	6.25
600 - 730	10.356	8.759
730 - 862	10.136	9.210

Note that, radiation patterns of a terrestrial broadcast antenna define the maximum power gain of the antenna in any specific direction. Antenna alignment describes the angular displacement of the transmitter-receiver pair's central axis. Such angles can either lie between (0 degrees and 360 degrees) in the azimuth direction or lie between (-90 degrees and 90 degrees) in the elevation direction. Polarisation of an antenna describes the orientation of the electric field of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna and its orientation. Strictly speaking in terrestrial broadcast planning, transmitter-receiver antenna pair's central axis should be pointing to each other and should have equivalent polarisation (e.g. both vertical and both horizontal). Accordingly, using the correct antenna gain patterns, antenna direction (azimuth and elevation) and antenna polarization is critical to planning to ensure that the maximum amount of signal power is transmitted to where the intended viewership population is located. **Fig. 3** illustrates a broadcast transmitting antenna.

Fig. 3. Horizontally polarised DTT transmitting antenna, azimuth 1050, frequency 706 MHz; the figure depicts an overlay of TV signal coverage prediction in Cape Town Central Business District, South Africa.

3.7 Terrestrial Broadcast Television Coverage Determination: Methodologies

The targeted large geographical area of interest is sub-divided into many smaller size geographical areas of typical resolutions (100 m×100 m, 200 m ×200 m); it is worth noting, however, that significant variations of field strength begin to be noticeable only at a distance of about 100 m [22]. Using a suitable propagation model, the quality of received coverage would vary from one location to another within these small areas due to the fading phenomenon caused by the local terrain and clutter. As a result of this received signal variation, a geographical area is considered covered if the median minimum field strength threshold has been exceeded at a large percentage of locations within a small area [22]. This signal spatial variability is corrected by a quantity known as location correction factor (CL). **Table 4** and **Table 5** depict the location correction factors and the wanted minimum median field strengths respectively. The FCC states that the minimum median field strength for DTT must be exceeded at 90% of locations and 50% of locations for ATT.

Table 4. Location correction factor for various percentages of location probabilities

$q(\%)$	$\sigma_w\ (dB)$	$\varphi_w\ (dB)$	$CL(q)(dB)$
1	5.5	-2.33	-12.8
5	5.5	-1.64	-9.0
10	5.5	-1.26	-7.0
50	5.5	0	0
70	5.5	0.524	2.88
90	5.5	1.28	7.0
95	5.5	1.64	9.0
99	5.5	2.33	12.8

Table 5. Band specific median minimum field strength values [23] and [24]. Median minimum field strength E_med for ATT frequency is exceeded at 50% of locations

Analogue Terrestrial TV (ATT)		
Frequency band (MHz)	Minimum median field strength (dBu)	
	Grade B contour	Grade C contour
VHF (Band III) 174-238/246-254	55	49
UHF (Band IV) 470-578	65	60
UHF (Band V) 582-862	70	60
Digital Terrestrial TV (DTT)		
Frequency band (MHz)	Location probability (q %)	Minimum median field strength (dBu)
470 - 502	95	52
558 - 630	95	54
710 - 790	95	56

The remainder of this section discusses dominant methods for predicting coverage.

- Minimum Coupling Loss (MCL) [25]: The MCL methodology takes a simplistic approach in predicting the required signal isolation necessary to establish coverage by the wanted transmitter in the presence a single interfering transmitter. The methodology does not take into consideration the effect of signal fading. Additionally, MCL assumes that the wanted signal power is above the wanted receiver sensitivity by a margin of 3 dB. The calculation of signal isolation is implemented in a simplified link budget format by adding up the wanted and interferer parameters. **Table 6** further illustrates this.

- Enhanced Minimum Coupling Loss (EMCL) [25]: The EMCL methodology predicts the required signal isolation between the wanted transmitter and multiple uniformly distributed interfering transmitters by taking into consideration the effect of signal fading. Moreover, EMCL does not assume a fixed margin of the wanted signal power above the wanted receiver sensitivity. Therefore the resulting signal isolation can be converted into distance or frequency separations as well as the probability of interference. Moreover, the methodology utilises a family of empirical propagation and interference curves [26]. Such curves define TV transmitting antenna height in metre; the field strength in dB above 1 μV/m for 1 kW, transmitter effective radiated power (ERP), and distance in kilometer.

That is a terrestrial broadcast TV channel should be sufficiently received if the field strength has been exceeded by the predefined percentages of time and location within a predefined small area [26].

- Statistically-based Methodologies: Statistical methods are best-suited approach to determine coverage in the presence of the signal fading phenomenon as well as the in the presence of multiple sources of interference. There exist several statistical methodologies, these include but are not limited to [27] and [28]: (1) Schwartz and Yeh: This is an approximation-based approach, which assumes that the sum of the moment of two interfering field strengths have lognormal distribution with location. (2) Power sum: This is an approximation-based approach that calculates the sum of the signal by using a non-statistical treatment of individual summands of signal powers. (3) Log normal: These are approximation-based approaches, which, statistically calculates the sum distribution of several individual summands of lognormal distributed variables. (4) Simplified multiplication: This is an approximation-based approach that statistically multiplies log normally distributed interfering signals in different locations. This approach does not consider the effect of noise. (5) Monte-Carlo (MC) simulations: This is the most accurate/efficient approach to evaluate the coverage in a small area/pixel. This is achieved by simulating a combination of a large number of victim links and interfering links pairs randomly distributed in multiple reception locations within a pixel. The median, mean and standard deviation of each event are

3.8 Analysis of Terrestrial Broadcast Television Coverage

There exist two distinct approaches used to analyse coverage, interference and population covered in small areas (the small areas are sometimes referred to as “pixels”). Both approaches are based on counting of pixels [22]. (1) Proportional counting: This approach is commonly used for planning terrestrial broadcasting networks specifically when assessing the impact of interference from non-broadcasting networks. The approach labels the location probability of pixels not covered as “zeroes” leaving the location probability of covered pixels untouched. The total coverage area is determined by averaging the sum of all location probabilities. (2) Black and White (B&W) counting: This approach is commonly used for planning terrestrial broadcasting networks specifically when assessing the impact interference from other similar broadcasting networks. The approach either labels the location probability of covered pixels as “ones” and the location probability of not covered pixels as “zeroes” or vice-versa. Similarly, the total coverage area is determined by averaging the sum of location probabilities. **Fig. 4** depicts the concept of small coverage areas.

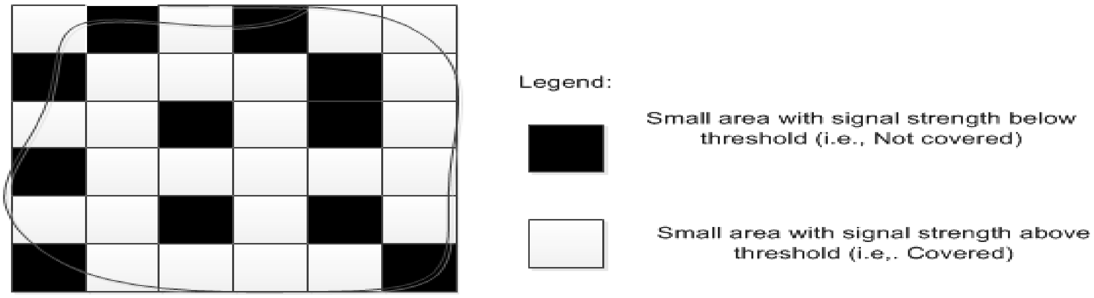

Fig. 4. An illustration of terrestrial broadcast TV coverage areas

4. Geo-location White Space Spectrum Database Parameters

This section discusses planning parameters key to all regulatory jurisdictions necessary for the implementation of GL-WSDBs. It is important to consider that a good radio planning practice would allow for a single terrestrial broadcast TV transmitter to provide fixed, portable outdoor and portable indoor reception in respective overlapping areas. Furthermore, it is important to consider that many countries particularly in the emerging and developing regions are still in the dual illumination phase (i.e., simulcasting of analogue and digital terrestrial broadcast TV signals).

4.1 Protection Ratios: White Space Device Emission into Terrestrial Broadcast Television

Protection ratios as discussed in sub-Section 3.4 are the ratios of wanted TV signal power over the unwanted WSD signal power at the point of failure of the receiving antenna. In light of protecting terrestrial broadcast TV receivers from potential harmful interference that might be generated by WSDs. Regulators have derived protection ratios for co-channel and adjacent channels specifically for various channel bandwidths. **Table 6** illustrates this.

Table 6. Terrestrial broadcast TV receiving antenna protection ratios against WSDs as per Ofcom of UK and FCC of USA.

Regulatory body: Ofcom, UK (Class 1 WSD) [29]	
Channel bandwidth	8 MHz
Channel type to be protected	Protection ratio (dB)
Co-channel ($\Delta F = 0$)	17
Adjacent channel ($\Delta F = \pm 1$)	-36
Regulatory body: FCC, USA [30]	
Channel bandwidth	6 MHz
Channel type to be protected	Protection ratio (dB)
Co-channel ($\Delta F = 0$)	23
Adjacent channel ($\Delta F = \pm 1$)	-33

4.3 White Space Device Spectral Emission Mask

This parameter depends on the regulatory jurisdiction. The spectral mask is used to define the maximum permitted out-of-band (OOB) emissions for operation of WSDs in the VHF and UHF TV bands. **Fig. 5** depicts a typical mask.

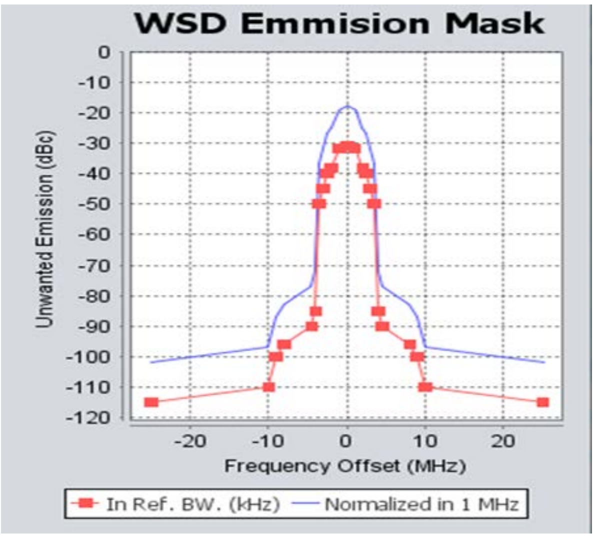

Fig. 5. Typical WSD spectral emission mask, the key factors for the determination of the mask for a particular frequency band are the total emmision power of a WSD in dBc and the reference bandwidth. In this example, the inner curve (also known as actual curve) is referenced at a given bandwidth of 50 kHz. The outer curve (also known as normalised) is normalised at a reference bandwidth of 1 MHz. The normalised normalised curve is the one used in the actual OOB calculation of WSDs as it provides a buffer offset from the actual curve.

4.4 Radio Propagation Modeling

Antenna heights of different classes of WSD range from less than 1.5 m HAAT up to 250 m HAAT. Additionally, since separation distances between WSDs and the terrestrial broadcast TV contours can range from less than few metres up to tens of kilometer. Regulators utilise appropriate propagation models for each scenario in order to accurately calculate the impact of WSDs on TV reception (various propagation models are discussed in **Table 1**).

5. Review of Geo-location White Space Spectrum Database Implementation Methodologies

Regulators are not supposed to dictate the technical methodology for the implementation of the GL-WSDBs. In reality, however, it is challenging to separate radio regulation frameworks from technical implementation aspects of RF stations that wish to operate in the TV bands on a non-assignment basis. Leading national regulators have shown their preferences on different technical methodological implementation of the GL-WSDB [29], [30], [31], [32] and [33]. This Section highlights dominant GL-WSDB implementation methodologies.

5.1 Vectorised Approach

This is a MCL-based methodology that largely relies on rigid rules of separation distance vectors to each grade of terrestrial broadcast TV contour in order to determine the availability of TVWS channels. The separation distance vector calculations are performed using the field strength propagation and interference curves and appropriate propagation models. This is a preferred approach by both the federal communications commission (FCC) of the USA [30], and the Industry Canada [31]. The algorithm consists of three main parts:

1. *For all technology types of incumbent stations:*
   1.1. *Using appropriate propagation model perform calculation of signal strength coverage for each contour grade in the geographical area of interest.*
2. *For each class of WSD {Transmit power, Antenna HAAT}:*
   2.1 *Using appropriate propagation model or curves perform calculation of separation distances from the edge of each incumbent contour grade.*
3. *For each test point of interest {WSD's geo-location, HAAT & all VHF/UHF channels}:*
   3.1 *Calculate and analyse available TV white space channels based on the contour separation distances and protection ratios.*
   3.2 *Hence, a channel is available if a WSD is outside of the separation distance.*

5.2 CNIR Threshold Approach

This is basically an EMCL-based methodology; the approach compares the received signal power level within a small geographical area of interest (pixel) in each channel against the minimum CINR threshold to determine if a channel is occupied or not occupied [27]. Process is repeated across all pixels. The algorithm consists of three main parts:

1. *For all technology types of incumbent stations:*
   1.1. *Using appropriate propagation model perform calculation of received signal power levels in all channels within a small geographical area (pixel) of interest.*
2. *For all channels in a small geographical area of interest (pixel):*
   2.1 *Compare the received signal strength against the minimum CINR threshold.*
   2.2 *Hence, a channel is occupied if the received signal strength power level is above the minimum CINR threshold. Otherwise a channel is available*
3. *For all available channels in a small geographical area of interest (pixel) and WSD's HAAT:*
   3.1. *Calculate and analyse maximum allowed WSD transmitting power levels based on the protection ratios and adjacent channel selectivity threshold.*

5.3 Degradation of Location Probability Approach

This is a statistical approach that utilise MC simulations methodology to determine the degradation in location probability of a DTT receiver in small geographical coverage areas (pixels). Any presence of WSD interfering signal within a pixel reduces the location probability of an incumbent receiver. This degradation is subsequently used to calculate the availability of TV white space channels. This is a preferred methodology by the Ofcom of UK [29] and the European Conference on Postal and Telecommunications Administrations (CEPT) [33]. The algorithm consists of four main parts:

1. *For all technology types of incumbent stations:*
    1.1. *Using appropriate propagation model and MC simulations perform calculation of location probability in each geographical small area (pixel) "before" the introduction of an interference signal (i.e., in the presence of system noise only).*
2. *For all technology types of incumbent stations and for each class of WSD {Transmit power, Antenna HAAT}:*
    2.1. *Using appropriate propagation model and MC simulations perform calculation of location probability in each geographical small area (pixel) "after" the introduction interference signal.*
3. *For each small area (pixel):*
    3.1. *Using MC simulations perform calculation of the maximum permitted degradation (change) in location probability that is:*
    $\{\Delta_q = q_{before} - q_{after}\}$.
    3.2. *Therefore the permitted change in location probability is set as the threshold* $\Delta_q = E_u$
4. *For each test point of interest {WSD's geo-location & all VHF/UHF channels}:*
    4.1. *Calculate and analyse maximum allowed WSD transmitting power levels based on the protection ratios and adjacent channel selectivity threshold.*

Where:

E_u = *Usable field strength that is defined as defined as the field strength of wanted signal required for achieving a desired signal quality. This is obtained by the power sum of the multiple interfering signals and the required protection ratios*

5.4 Summary

The key differences between the approach described in sub-section 5.1 and the approaches described in sub-Sections 5.2 and 5.3 are the fact that the former only allows operation of WSDs at a safer distance outside the broadcast TV contour while the latter allows operation of WSDs within the broadcast TV contour.

6. Practical Implementation

This section, discusses a real-world implementation of a GL-WSDB developed for the South African territory by the CSIR-Meraka Institute. South Africa belongs to ITU region 1 within which each television channel occupies an 8 MHz band. According to the current South African frequency allocation table [34], the following entities will require immediate protection from the operation of WSDs in the TVWS: (1) TV stations in the 174-234 and 474-854 MHz bands. (2) Public trunking, maritime radio- navigation, short-range devices (SRDs), and wireless microphones in the bands adjacent to 174-234 MHz band. (3) Mobile/fixed services in bands adjacent to the 474-790 MHz band. (4) Radio-astronomy in the 608-614 MHz band. Of the above–listed entities to be protected, the most readily available information from the Independent Communications Authority of South Africa (ICASA), only describes parameters for protecting TV stations. The minimum usable field strength values used to calculate service coverage for ATT and DTT services in bands III, IV and V are listed in **Table 5**.

6.1 Problem Statement

The key problem is how to construct a GL-WSDB for South Africa capable of calculating and availing WS channels for the secondary usage in the VHF and UHF TV bands at any given location and time without causing harmful interference to the primary users. The available WS channels should be available to the WSDs with different antenna heights and different transmitting powers levels.

6.2 Motivation for the Implemented Approach

It is worth noting that South Africa does not yet have TVWS regulations of her own, as such a conservative MCL methodology taking into account the 8 MHz TV channel width used in ITU region I, has been chosen in this implementation. MCL is preferred because it provides robust protection to the primary users in the both grade B and grade C coverage contours. For example, users in marginal areas who cannot receive grade B quality can still be protected under grade C contours. Many rural users in Africa are located in these fringe reception areas and make do with fairly poor reception quality or do their best to improve their reception by raising their mast height beyond the norm. The degradation of location probability methodology was not preferred because of lack of a reliable national dwelling address system that corresponds with the location TV license holders. In South Africa it is a norm to find several TV license holders living in one house; this could inhibit the process of identifying the location of TV receivers to be protected. Likewise, the CNIR threshold approach was not preferred because it is not reliable enough to protect marginal primary users at the edge of the coverage contours. Due to its heavy reliance of comparing the received signal power levels with the threshold; the approach can easily expose primary users to an interference situation similar to the hidden node problem common to spectrum sensing devices. The implementation utilised three wave propagation models for coverage contours and separation distance calculations. The choice of propagation models considered the following facts: (i) South Africa belongs to the ITU region 1 (ii) the wide varying geographical terrains ranging from forests, grasslands, deserts, low-lying coastal areas to mountains. The three wave models chosen are: (1) The Irregular terrain with obstruction model (ITWOM) **[19].** This model combines ITM Longley-Rice **[17]** and ITU-R P.1546-x [22]. By utilizing a digital elevation model (DEM) database of choice **[35]**, ITWOM can accurately calculate terrain roughness factor "delta-h" and losses close to the obstructions along victim system link path (incumbent stations) and interference system link path (WSDs) as such reduces the overall over-estimation and under-estimation of available white space spectrum. ("delta-h" is an important factor used to set the ratio of rounded edge to knife edge diffraction in the diffraction range as well as the diffraction losses versus two-ray in line of sight range). (2) The FCC/OET TM 91-1 **[18]**, is preferred because it is more accurate for wave propagation predictions in shorter distance paths (i.e., below 1 km) in sub-urban environments akin to those found in South Africa and for shorter antenna heights (i.e., up to 30 m). (3) The R-6602/FCC-Curves **[7, 30]** modified to accept ITU region I grade B and grade C contours. In our approach all WSDs antennas were treated as Omni directional, this is attributable to the fact that different wireless Internet service providers (WISPs) could procure and deploy different polar types of WSDs antennas in their respective networks without our knowledge, as they so wish. However, TV receivers were considered to be pointing towards the desired TV stations and their back-lobes pointing to the direction of WSDs. Therefore, polarization mismatch loss was not considered but rather a 14 dB front-to-back ratio. All incumbent transmitters were treated as either vertical polarized, horizontally polarized or Omni directional this depended on the planning data obtained from the regulator.

6.3 Step-by-Step Implementation

In principle, the GL-WSDB performs the following operations:

❖ Calculation of incumbents contour distances:

Step 1: Identify the TV stations of interest

South Africa is still in dual illumination period (this is a transition period from analogue TV transmission technology to digital TV transmission technology of which a particular country utilises both TV transmission technologies simultaneously). There exist over 1000 entries of incumbent stations in the terrestrial broadcast frequency plan; (operational and planned high power and gap-filler DTT multiplex sites and analogue sites). The planning data is obtained from the regulator (ICASA) [34]. We are considering an interference limited contour (ILC) mode in a multi-frequency network (MFN) structure with single transmitting tower at each site. We therefore distinguish each entry by a combination of frequency assignment in use (in VHF and UHF bands,) and site name. Additionally, we distinguish each TV channel based on the technology type (i.e., analogue and digital) as this is one among important factors when protection ratios against WSDs are applied in the calculations as the two technology types use different protection ratio values. One should note that in the case of a SFN structure only a noise limited contour (NLC) and DTT protection ratio could have been applied in the calculations. We initially prepare and load this data together with other relevant technical information of each TV station into a relational database. For each snapshot of calculation, the focus is however placed only on a particular area of interest (i.e., within and around the area relative to the WSD's present location at that particular time.) That is, the GL-WSDB must identify all incumbent stations present in a radius of interest within which a WSD might potentially cause harmful interference and cull the incumbent stations outside this area of interest. The significance of culling procedure for each snapshot is the reduction of computational time as opposed to when the entire database of transmitters is used each time. The GL-WSDB implements Haversine point-to-point geodesic great-circle distance formula to find the minima and maxima of the bounding box. Haversine function is based on the location coordinates (latitude and longitude) of the desired transmitter sites and receiver sites; the function remains reasonably accurate for the shortest path calculations over the earth surface. The formula is based on spherical earth assumption and it is accurate for distances up to 475 km. This function is relevant in our implementation since our anticipated maximum culling distance is only 300 km for each snapshot:

$$Hv\left(\frac{d}{R}\right) = Hv(lat_1 - lat_2) + \cos(lat_2)Hv(\triangle\, lon) \qquad (1)$$

where:

Hv:	Haversine function
d:	Spherical distance between two points in km
R:	Radius of sphere in km
lat:	Latitude in radians
$\triangle\, lon$:	Change in longitude in radians

Fig. 6. depicts the how TV transmitters of interest are being identified.

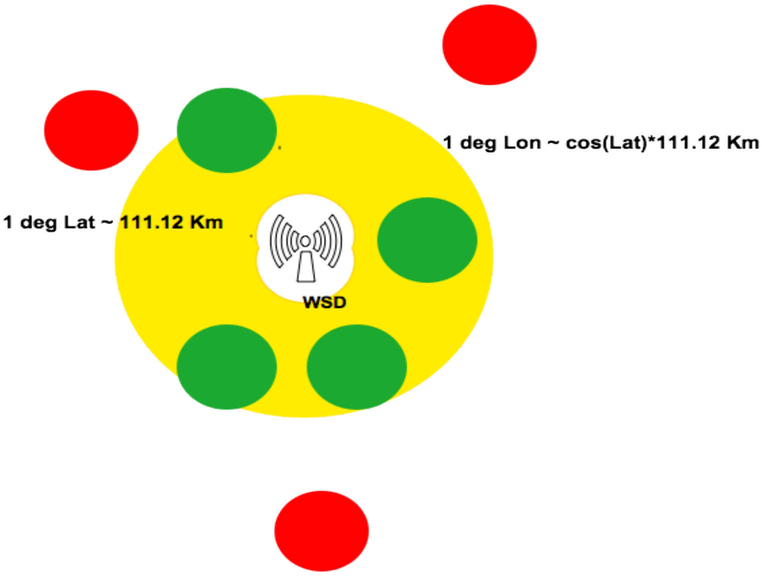

Fig. 6. An illustration of TV stations culling: green circles represent a snapshot of TV stations within a given boundary of interest relative to the WSD location. Red circles are station not to be considered in the snapshot.

Step 2: Calculate antenna HAATs of incumbent stations
The GL-WSDB utilises the geo-location of the identified TV stations of interest in **Fig. 6**. Calculates HAAT of each identified TV station taking into consideration the surrounding terrain profile within a distance of 3.2 km to 15 km. The resulting HAAT pattern is a plot obtained from the evenly spaced increment of 2.50 starting from (00 as true North) to 3600. Corresponding numerical values for each degree increment is also obtained. The antenna's radiation center above mean sea level (RACMSL) is also obtained. The GL-WSDB utilise 3-arc-second digital terrain data to perform this operation [35].

Step 3: Derive the relative field value(s)
The typical normalised relative field value of an antenna is approximated to be 0.707 at Half Power Bandwidth (HPBW). Alternatively, The GL-WSDB calculates the relative field value by using the TV station transmitting antenna depression angle. The depression angle is linearly interpolated in the VHF/UHF antenna vertical patterns graph to extrapolate the corresponding normalised relative field value [36].

Step 4: Calculate the radial ERP
The radial ERP in kilowatt is a product of maximum ERP of the TV station and the square of the normalised relative field value:

Step 5: Convert the radial ERP obtained in (Step 4) into radial power in decibel referenced to 1 Kw.

Step 6: Calculate the radial field strength
For each frequency band TV of operation. The GL-WSDB subtracts the radial power obtained in (Step 6) from the appropriate protected contour field strength values specified in **Table 5**.

Step 7: Interpolate the contour coverage distances (contour grade B and contour grade C) of each TV station of interest as a function of field strength. The GL-WSDB log-linearly interpolates the contour distance using ITWOM/ITU-R P.1546-5 propagation model [26] at 95% locations and 50% time:

$$D_c = D_{inf}\left(\frac{D_{sup}}{D_{inf}}\right)^{\Delta E} \quad (2)$$

given that $\Delta E = \left(\mathrm{E} - E_{inf}\right) \times \left(E_{sup} - E_{inf}\right)$, where:

D_c: Contour coverage distance in km
E_{inf}: Nearest field strength value below E_r in dBu
E_{sup}: Nearest field strength values above E_r in dBu
D_{inf}: Distance value for E_{inf} in km
D_{sup}: Distance value for E_{sup} in km

❖ Calculation of incumbents contour separation distances:

Step 8: Utilise TM-91-1 [18] propagation model and protection ratios for calculation of shorter separation distances at shorter WSD antenna heights. Since the WSD field strength is the difference between the protected contour median field strength and the protection ratio. The TM-91-1 formula is therefore re-arranged as follows:

$$E_{WSD} = 141.4 + 20\mathrm{Log}_{10} h_1 h_2 - 40\log_{10} D_{sep} + 10\log_{10} P_{WSD} + FB \quad (3)$$

where:

E_{WSD}: Field strength of WSD in dBu
CIR: Incumbent's protection ratio for co-channel and adjacent channel in dB
h_1, h_2: RCAMSL of antennas in m
P_{WSD}: Effective radiated power of WSD in W
FB: TV receiver front-to-back ratio in dB
D_{sep}: Contour separation distance in m

Likewise, utilise ITWOM/ITU-R P.1546-5 interference models at 50% of locations and 1% of time and protection ratios for calculation of longer separation distances at longer WSD antenna heights. **Table 7** illustrates the calculated separation distance of various classes of WSDs.

Table 7. Selected WSD antenna HAATs, incumbent contour separation distances and transmit power constraints. The calculation of separation distances is described in step 8.

WSD antenna HAAT (m)	WSD transmit EIRP (dBm)	Incumbent contour separation distances (km)	
		Adjacent channel	Co-channel
< 3	36	0.260651739	4.635116213
3 < 10	36	0.532988726	8.462525688
10 < 30	36	0.923163553	10.8
200 - 250	36	3.575397067	33.6

❖ Calculate the available TVWS channel(s):

A high-level flow-chart in **Fig. 7** illustrate a sample implementation utilizing WSD transmit power and incumbent contour separation distance constraints parameters shown in **Table 7**. The GL-WSDB should avail TVWS channels under the following conditions: A WSD must be operating within 1.2 km or beyond the protected contour for adjacent channels. Similarly, free co-channels will be made available if the WSD is operating within 11.1 km or beyond. These distance values used are for illustration purpose only.

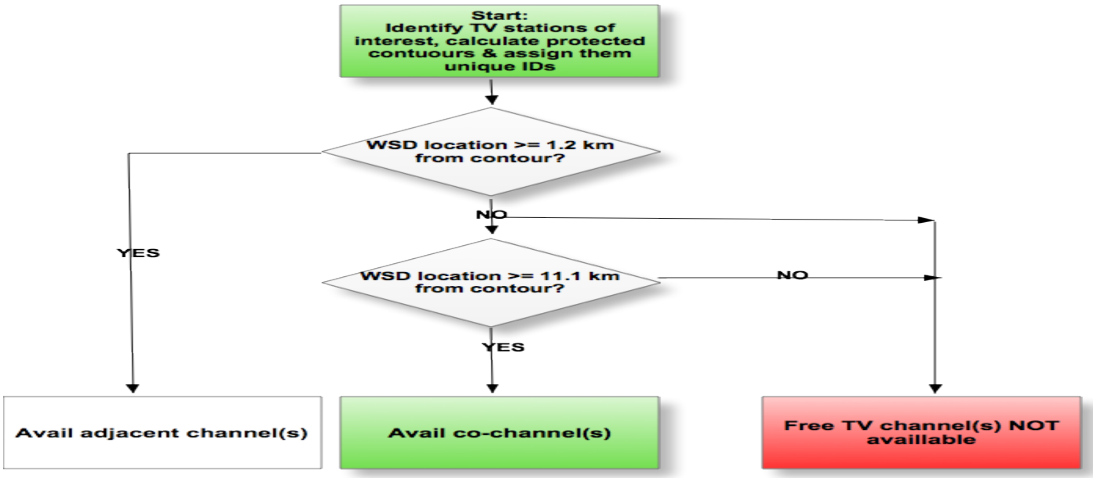

Fig. 7. High-level illustration of channel availability flow chart, values used are for illustration purpose only

7. Results Discussion

We took a rather conservative approach during the calculation of the distance to protected contours for ATT stations. We chose to include the minimum median field strength values prescribed for both grade B and grade C service areas. This is attributable to the fact that some of the TV viewers in the rural communities particularly those located further beyond the edges of the protected grade B service coverage areas would still wish to receive TV broadcast using extended outdoors antennas (longer than 10 metre). Such conservatism approach to some extent can lead into much larger protected TV broadcast service areas. **Table 8** lists and, **Fig. 8a)** and **Fig. 8b)** depict results of maximum available TVWS channels and contiguous bandwidth for the entire South Africa.

Table 8. Snapshot depicting available TVWS channels and contiguous TVWS bandwidth per local South Africa municipality. Population data is obtained from Statistics South Africa [37].

Province	Local municipality	Number of TVWS channels	Maximum available contiguous bandwidth (MHz)	Population	Population density (km/sq.)
Western Cape	Beaufort West	25	104	49,586	2
Eastern Cape	Blue Crane Route	40	64	36,002	3
Gauteng	Mogale City	39	112	362,422	270
Mpumalanga	Bushbuckridge	28	104	541,248	53
Limpopo	Ba-Phalaborwa	45	128	150,637	20
KwaZulu - Natal	Ezingoleni	45	256	52,540	81

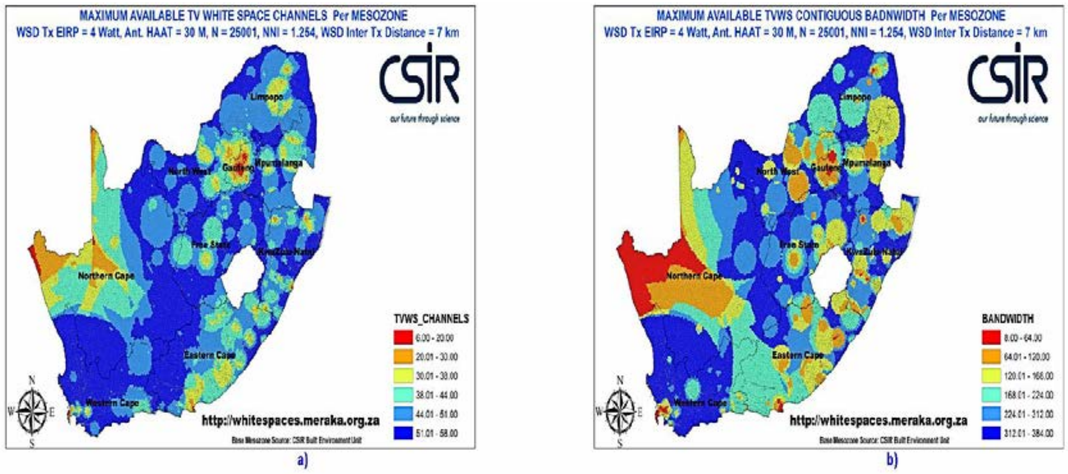

Fig. 8a) Heat map depicting maximum available TVWS channels in South Africa's mesozones (mesozones are small irregular areas of appromately 7km square, South Africa is sub-divided into 25001 such mesozones (N)).In this scenario fixed WSD EIRP was set at 4 watt with antenna HAAT set at 30 m. One WSD was placed at the centre of each mesozone with an inter-WSD separation distance of 7 km. Mesozones nearest neighbour index (NNI) was 1.254. **Fig.8b)** Heat map depicting maximum available maximum contiguous TVWS channel bandwidth in South Africa's mesozone this scenario used similar settings of WSD as in **Fig. 8a)**.

8. Results Evaluation

This Section evaluates results of our GL-WSDB implementation using two methods: Firstly by performing a comparison of the percentage of identical available WS channels against a selected commercially available GL-WSDB, and secondly by performing a comparison of available identical WS channels against spectrum occupancy scans measurements in the field.

8.1 Test bed Setup

Our implemented GL-WSDB is running in an IBM e1350 Linux cluster virtual machine hosted at the Centre for High Performance Computing (CHPC). This can be accessed via the following URL: http://whitespaces.meraka.org.za [38].

8.2 Results Evaluation against Commercially available GL-WSDB

This sub-Section compares results of our implementation [38], shown in **Fig. 9**, with a commercially available GL-WSDB [39], shown in **Fig. 10**. We introduced the term *percentage of similarity* as the sum of all available identical channels found in both systems (i.e., from the commercially available GL-WSDB and from our GL-WSDB implementation), over the sum of all channels found in both systems. For the purpose of this comparison, our implementation uses FCC-Curves [7, 30] model modified with ITU region I grade B contour in **Table 5**. To the best of our knowledge the commercially available GL-WSDB utilises FCC-Curves [30] model with FCC contours (I.e. 36 dBu for the VHF band and 41 dBu for the UHF band) used in the North America. The channels are to be available for a 4 watt fixed WSD with an antenna height AGL of 30 metre. Moreover, the comparison has been done for five cities in South Africa: (Johannesburg, East London, Polokwane, Durban, and Bloemfontein). The overall average percentage of similarity is 68%. Results are presented in

Table 9. The difference in the type of contours used by the two systems is confirmed by the results obtained. The commercially available GL-WSDB produced fewer channels in most occasions due to the larger protected FCC contours as compared to the smaller ITU region I grade B contour (see **Table 5**). The results underscore an important aspect for national regulators particularly in the developing countries to enforce jurisdiction-based rules for the operation of GL-WSDBs.

Fig. 9. CSIR-Meraka GL-WSDB using FCC-Curves wave propagation model showing 3 available channels (UHF channels 41, 62 and 66) for a 4 W fixed WSD with antenna HAAT of 50 m to 75 m in Johannesburg area, South Africa [38].

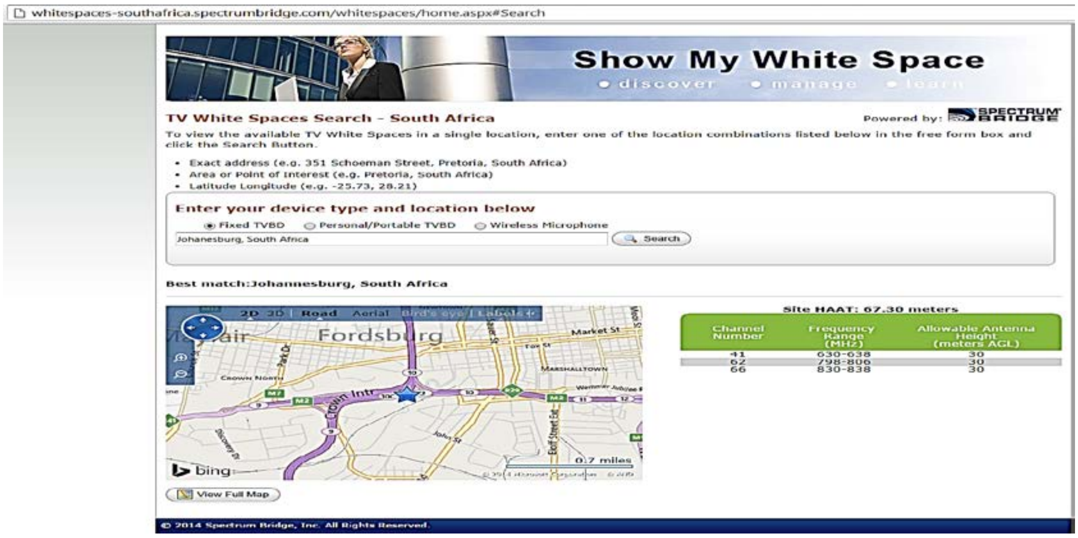

Fig. 10. A commercially available GL-WSDB using FCC-Curve wave propagation model showing 3 available channels (UHF channels 41, 62 and 66) for a fixed WSD with antenna height of 30 m AGL, with HAAT of 67.30 m in Johannesburg area, South Africa [39].

Table 9. Comparison between CSIR-Meraka's GL-WSDB [38] and commercially available GL-WSDB [34] for the available TVWS channels in five South African cities for a 4 W fixed WSD at 30 m transmitting antenna height

City	System	Available TVWS Channel Number per System	% of Similarity
Johannesburg	CSIR-Meraka GL-WSDB	41, 62, 66	100
	Commercial GL-WSDB	41, 62, 66	
East London	CSIR-Meraka GL-WSDB	11, 21, 22, 24, 25, 26, 27, 28, 29, 30, 32, 33, 34, 38, 39, 40, 41, 42, 43, 44, 47, 48, 49, 56, 57, 59, 60, 61, 67, 68	47
	Commercial GL-WSDB	11, 21, 22, 23, 25, 26, 27, 28, 29, 30, 34, 38, 39, 40, 41, 47, 51, 52, 56, 60, 64, 66	
Durban	CSIR-Meraka GL-WSDB	36, 38, 33, 40, 44, 46, 48, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65,66,67,68	67
	Commercial GL-WSDB	53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65,66,67,68	
Polokwane	CSIR-Meraka GL-WSDB	21, 22,23,30, 31, 32, 36, 37, 38, 39, 40, 41, 42, 46, 47, 48, 49, 50, 51, 52, 53, 54, 58, 62, 66	57
	Commercial GL-WSDB	21,25,29, 30, 31, 32, 36, 37, 38, 39, 40, 41, 42, 46, 50, 54, 66	
Bloemfontein	CSIR-Meraka GL-WSDB	4, 11, 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 36, 37, 38, 42, 46, 50, 55, 56, 57, 59, 60, 61, 65, 66, 67, 68	71
	Commercial GL-WSDB	4, 11, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 35, 36, 37, 38, 42, 50, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67	
		Average overall Percentage of Similarity	68

8.2 Results Evaluation against Field Spectrum Scan Measurements

This sub-section compares results of our implementation [38] with spectrum occupancy field measurement scans [40]. All field scan measurements were done in a vertical polarisation, no polarisation mismatch losses were considered since all stations were transmitting in vertical polarization**. Fig. 11** shows 37 available TVWS channels in the VHF and UHF bands (channels 4, 6, 7, 9, 10, 13, 24, 29, 31, 32, 36, 37, 39, 40, 41, 43, 44, 45, 47, 48, 52 to 68), these were calculated by our GL-WSDB. The channels are available at Settlers primary school, Cape Town, South Africa. The channels are available for a 1 watt fixed WSD with an antenna HAAT of between 3 metre and 30 metre.

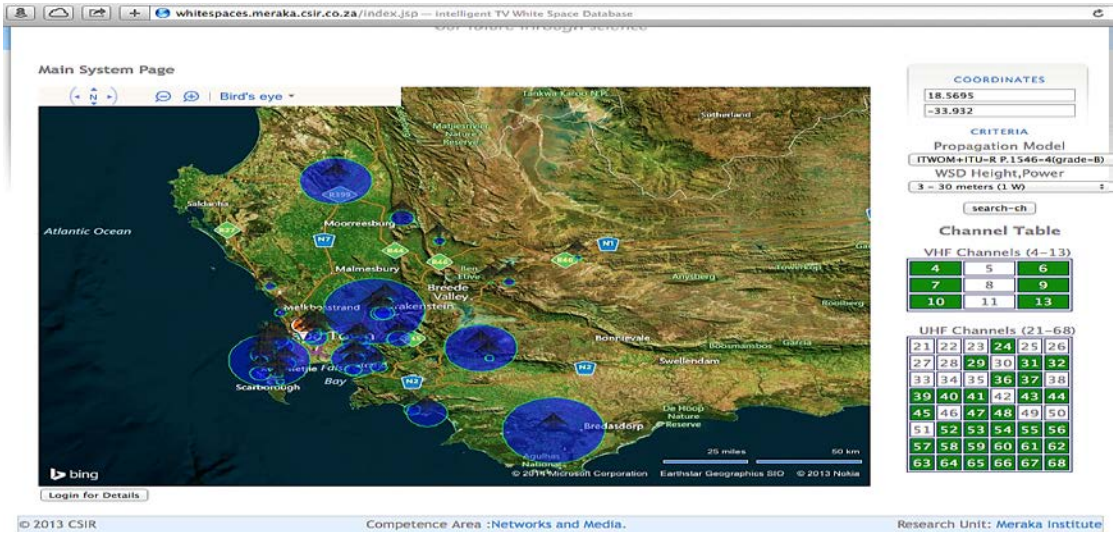

Fig. 11. CSIR-Meraka GL-WSDB using ITWOM wave propagation model showing 37 available TVWS channels (VHF and UHF channels 4, 6, 7, 9, 10, 13, 24, 29, 31, 32, 36, 37, 39, 40, 41, 43, 44, 45, 47, 48, 52 to 68) for a 1 W fixed WSD with antenna HAAT of 3 to 30 m at Settlers primary school, Cape Town, South Africa [38].

Fig. 12 a) shows results of the spectrum occupancy field measurement scans performed at Settlers primary school and **Fig. 12 b)** shows results of spectrum occupancy measurements scans performed at hilltop Stellenbosch both sites are located in Cape Town, South Africa [40]. At Settlers primary school, 3+2 scans with each scan lasting for about 12 minutes were performed on the UHF channels 21 – 68. The type of antenna used was AntennaCraft ST4 (Omnidirectional discone outdoor TV antenna). The antenna was installed at 13 metre AGL. Rhode & Schwartz PR100 spectrum analyser was used to capture the measurements. At hilltop Stellenbosch, Cape Town, the plot depicts signal strength measured at four different directions (0^0, 90^0, 180^0 and 270^0) in the UHF channels 21-68. The type of antenna used was enclosed directional Rhode & Shwartz HE300 captured with Rhode & Shwartz PR100 spectrum analyser. The antenna was installed at 13 meters AGL however; the ground elevation of this particular site was higher than the first site at Settlers primary school. In both measurement sites the scans suggested that the following 25 UHF channels might be available (channels 21, 23, 25, 27, 29, 31-32, part of 33, 35, 36, part of 37, 39-41, part of 43, part of 44, 49, 51-55, 57, 61, and 63).

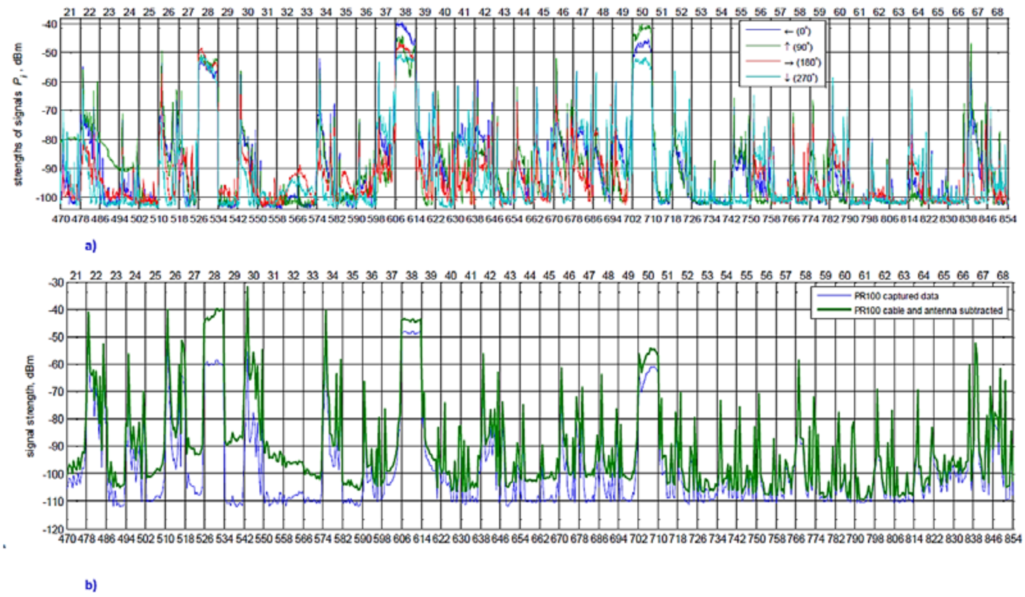

Fig. 12a) Results of channel occupancy scan measurements done at hilltop Stellenbosch, Cape Town, South Africa (latitude:-33.90778, longitude: 18.7782), the plot depicts signal strength measured at four different directions (0^0, 90^0, 180^0 and 270^0) in the UHF channels 21-68. The type of antenna used was enclosed directional Rhode & Shwartz HE300 captured with Rhode & Shwartz PR100 spectrum analyser **[40]**. **Fig. 12b)** Results of channel occupancy measurement data obtained at Settlers primary school, Cape Town, South Africa (latitude:-33.89764, longtude:18.60821). 3+2 channel scan measurements were performed on the UHF channels 21 – 68, each scan lasted for about 12 minutes. The type of antenna used was AntennaCraft ST4 (Omnidirectional discone outdoor TV antenna) captured with Rhode & Schwartz PR100 spectrum analyser. The curve “captured data” depicts raw data as capture by the spectrum analyser and the curve “cable and antenna substracted” depicts the final estimate as the cable losses and antenna gain have been substracted from the raw data. In both measurement sites the RCAMSL of antenna was at 13 m AGL [40].

The overall comparison shows that 16 out of the 25 UHF channels obtained in the field measurement are also found in the GL-WSDB UHF results. This result confirms what is known about the limitations of sensing at a single point where a WSD would wish to operate. Some of the channels that appear available on the spectrum scan would prove to be unavailable if spectrum analysis was done in other nearby sample points in the area. Likewise, due to the presence of low-power gap-filler stations that reuse channels at distant inter-transmitter distances but within the GL-WSDB culling distance, the GL-WSDB is able to avail TVWS channels that are not locally detected by the spectrum measurement scans. This paper did not consider the following issues: (1) protected distance contours required to mitigate cross-border interference with TV stations from five countries bordering South Africa (Lesotho, Swaziland, Botswana, Mozambique, and Zimbabwe). (2) Protection of wireless microphones. Future and ongoing work includes but is not limited to: expansion of a GL-WSDB to cover the entire Southern African Development Community (SADC) region and beyond. Improve accuracy of GL-WSDB by incorporating measurements results **[6],** as well as consideration of asymmetric fading environment in the interference system link path and victim system link path **[41].**

9. Conclusion

In this paper the functional position and role of the geo-location spectrum database (GL-WSDB) as a coexistence planner and manager between primary and secondary users within the terrestrial broadcast TV networks has been explained. Furthermore, the practical design process of a GL-WSDB for South Africa was described. The results produced by the implemented GL-WSDB were evaluated using two methods. First, results were compared against a commercially available GL-WSDB using FCC-Curves model; where an overall 68% of similarity for the available TVWS channels was found. The results were for a 4 watt fixed WSD at a 30 metre antenna height located at five cities in South Africa: Johannesburg, East London, Polokwane, Durban, and Bloemfontein. Furthermore, the difference in the type of contours used by the two systems is confirmed by the results obtained. The commercially available GL-WSDB produced fewer channels in most occasions due to the larger FCC contours (36 dBu and 41 dBu) used in the North America as compared to the smaller ITU region I grade B contour (55 dBu, 65 dBu, and 70 dBu). A result of Johannesburg agreed by 100% while that of East London was below 50%, further investigation is still required. The overall results underscore an important aspect for national regulators particularly in the developing countries to enforce jurisdiction-based rules for the operation of GL-WSDBs.

Secondly, the results of the GL-WSDB for a 1 watt fixed WSD were evaluated against field spectrum occupancy measurements. The results showed that 64% of channels in the UHF band agree with those of a spectrum scan at two specific sample points in Cape Town. It is important to note that GL-WSDB conservatively avails TVWS channels in a given geo-location and time by using an appropriate wave propagation model while applying the following constraints: (1) the WSD antenna height above average terrain (HAAT), (2) WSD transmitting power, (3) the incumbent protection ratios and, (4) the contour separation distance. The constraints are outlined in **Table 7**. The results confirmed that field measurements are the best way to validate spectrum occupancy since wave models are sometimes susceptible to under-estimation or over-estimation of spectrum occupancy. However, it is challenging and very expensive to perform real-time measurements for large geographical areas. Proper application of models coupled with correction factors, terrain profile modelling, and snapshots of static field measurements can enhance the design and accuracy of GL-WSDBs.

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